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Revised Guidelines for Designing Median Openings to Accommodate Simultaneous Left Turns

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Revised Guidelines for Designing Median Openings to Accommodate Simultaneous Left Turns

by S. Hadi Khazraee and H. Gene Hawkins, Jr.

ABSTRACT

When designing median openings at divided highway intersections, it is important to consider the impacts of simultaneous (non-crossing) left turning movements by vehicles from opposing directions. As the median opening (measured along the centerline of the divided highway) increases, the ability to accommodate simultaneous left turns increases. The AASHTO *Green Book* recommends minimum lengths of median opening for different design vehicles and median widths. These minimum lengths are calculated based on assumed control radii for left turns from the divided highway into the crossroad and vice versa, and do not account for accommodation of simultaneous left turns. The *Green Book* minimum median opening lengths can prevent the capability for simultaneous left turns under certain circumstances. This study uses simulated vehicle turning paths to define the minimum conditions for accommodating simultaneous opposing left turns and proposes corresponding revisions to the *Green Book* guidelines. The new method consists of determining the required control radius as a function of median width and calculating the minimum length of median opening by equations based on geometric relationships. The paper also describes the limitation of the *Green Book* methodology in addressing median openings with left-turn lanes, which is resolved by application of the proposed method.

INTRODUCTION

There are many factors that impact the effective design of a median opening at a divided highway intersection. The median width, the length of median opening, and the shape of the median nose are three of the most significant. The combined effect of these factors will establish whether the opposing left turns from the divided highway cross paths or turn in front of each other. Simultaneous left turns (paths do not cross) are more common with narrower medians or long median openings. This paper focuses upon the combined effects of these three factors and recommends guidelines for providing for simultaneous left turns.

A Policy on Geometric Design of Highways and Streets (*Green Book*) (*1*) illustrates the pattern of simultaneous left turns in Figure 9-53 (replicated in Figure 1) and discusses the subject briefly by stating "Simultaneous left turns may be considered at an intersection of two major highways, but design for single lane simultaneous opposing trucks is generally impractical." and that "A design feature that can improve intersection operation is to provide a minimum clear distance of 10 ft between opposing left-turn movements within the intersection." The *Green Book* guidelines for the minimum length of median opening, however, do not necessarily accommodate simultaneous left turns. Considering simultaneous left turns involves simulation of vehicles turning paths and relatively complicated geometric analysis which might be beyond the designers' available resources. This paper aims to modify the *Green Book* guidelines for minimum design of median openings to account for accommodation of simultaneous left turns with the recommended 10-ft minimum clear distance.

In addition, the authors noted that although unspecified, the current *Green Book* recommendations for the minimum length of median opening (in Tables 9-25 to 9-28) are limited to median openings with no turn lanes. The proposed method will address this limitation and generalize the guidance for median openings with or without turn lanes.

Previous Research

In a recent study (*2*), the authors of this paper evaluated the *Manual on Uniform Traffic Control Devices* (MUTCD) (*3*) criteria for determining the number of intersections at a divided highway junction (a single intersection vs. two separate intersections). To establish the minimum requirements for operation as a single intersection, Khazraee and Hawkins (*2*) determined the geometric conditions in terms of the median width and opening length that would accommodate simultaneous left turns of opposing vehicles from the divided highway. In doing so, they used a setting similar to that used in the *Green Book* guidelines for the minimum design of median openings (as illustrated in Figures 9-55 to 9-58 of the *Green Book*). In this paper, the authors follow the same procedure but for a completely different purpose. In the previous paper, the analysis was concentrated upon traffic control at existing junctions, whereas in this paper, the objective is to modify the *Green Book* design guidelines on the median opening length to accommodate simultaneous left turns.

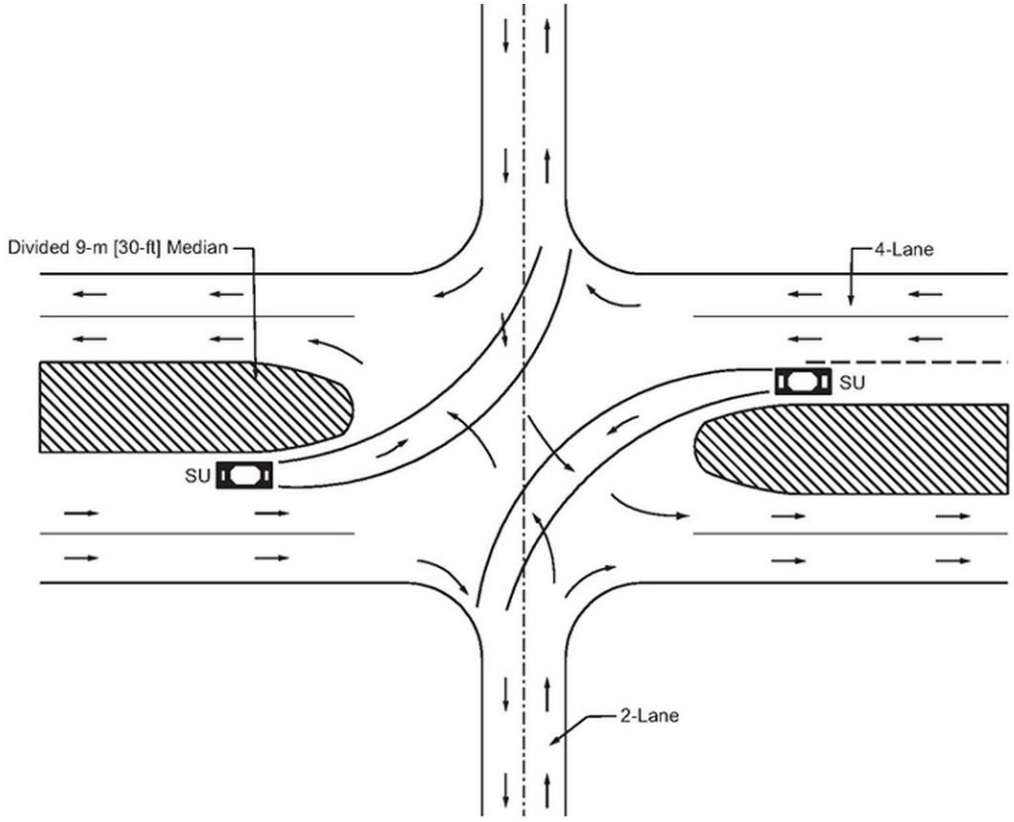


FIGURE 1. *Green Book* Figure 9-53: Four-leg intersection providing simultaneous left turns

REVIEW OF GREEN BOOK METHODOLOGY

Section 9.8 of *A Policy on Geometric Design of Highways and Streets* (*Green Book*) (*1*) contains guidelines about the design of median openings at divided highway intersections. Tables 9-25 to 9-28 of the *Green Book* prescribe minimum lengths of median opening at given median widths for different design vehicles and two alternate shapes of median ends (semicircular and bullet nose). The values in these tables are calculated based upon assumed control radii for minimum turning paths from the divided highway into the crossroad and vice versa.

The *Green Book* includes a methodology for calculating the minimum median opening length. Figure 2 replicates the *Green Book* Figure 9-57 which is one of the figures that illustrate the method for determination of the minimum median opening length (for WB-40 design vehicle). The *Green Book* minimum design of median openings is based on the minimum turning paths from the divided highway into the crossroad and vice versa. According to the *Green Book* methodology, the controlling dimension in determining the minimum median opening length is the radius of the 90-degree circular arc tangent to the median edge and the crossroad centerline. This radius, called the control radius, is indicated as R in Figure 2. For each design vehicle, the control radius is the radius of the "simple curve for the minimum assumed edge of left turn" (*1*). The *Green Book* determines the appropriate control radii based on two considerations:

1) Suitable accommodation of the design vehicle: the control radius arc should not be sharper than the inner rear wheels paths of the design vehicle (see *Green Book* Figure 9-54)
2) Accommodation of occasional larger design vehicles with some swinging wide

As such, the *Green Book* recommends the following control radii for minimum practical design of median openings for specific design vehicles: 40 ft (for passenger car (P)), 50 ft (for single-unit truck (SU-30)), 75 ft (for intermediate semitrailer (WB-40)), and 130 ft (for interstate semitrailer (WB-62)). Tables 9-25 to 9-28 of the *Green Book* contain the minimum recommended lengths of median opening for P, SU-30, and WB-40 design vehicles, respectively, while there is no corresponding table for the WB-62 design vehicle.

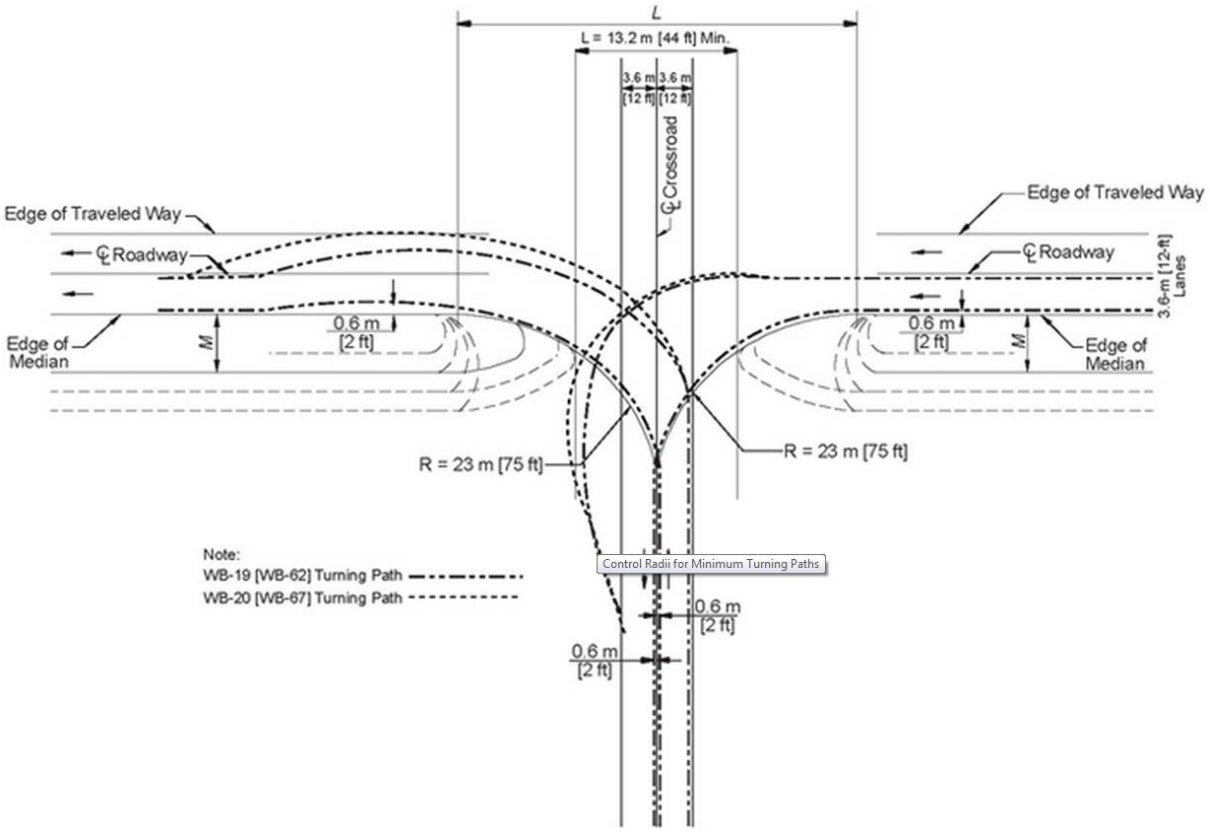


FIGURE 2. *Green Book* Figure 9-57: Minimum design of median openings (WB-40 design vehicle, control radius of 75 ft)

Once the appropriate control radius (R) is selected, the minimum required length of median opening (L) can be determined based on the given median width (M) and the shape of median ends (semicircular or bullet nose). Figure 3 demonstrates how the minimum median opening length is calculated. According to the *Green Book*, the point of curvature (PC) of the control radius arc is a common PC for both alternate forms of median ends. The bullet nose is formed by portions of two symmetrical control radius arcs and a nose rounded by an assumed small radius; the *Green Book* suggests 2 ft for the rounding radius and uses this assumption to calculate the minimum opening lengths in Tables 9-25 to 9-27. Thus, using basic geometric relations (as depicted in Figure 3), the minimum median opening length can be calculated as:

$$L = 2R - 2 \times 0.5M \quad \text{(for semicircular median ends)} \qquad \text{(Eq. 1)}$$

$$L = 2R - 2\left[\sqrt{(R-2)^2 - (R-0.5M)^2} + 2\right] \quad \text{(for bullet nose median ends)} \qquad \text{(Eq. 2)}$$

where all variables are as defined before. In addition, the *Green Book* recommends that the length of median opening should not be less than certain minimums: 56 ft for P and SU-30, 44 ft

for WB-40, and 40 ft for WB-62 design vehicle. Figure 4 combines the two criteria and presents the minimum required opening lengths graphically (rather than the tabular format in the *Green Book*). In Figure 4, the *Green Book* recommended values are shown with dots.

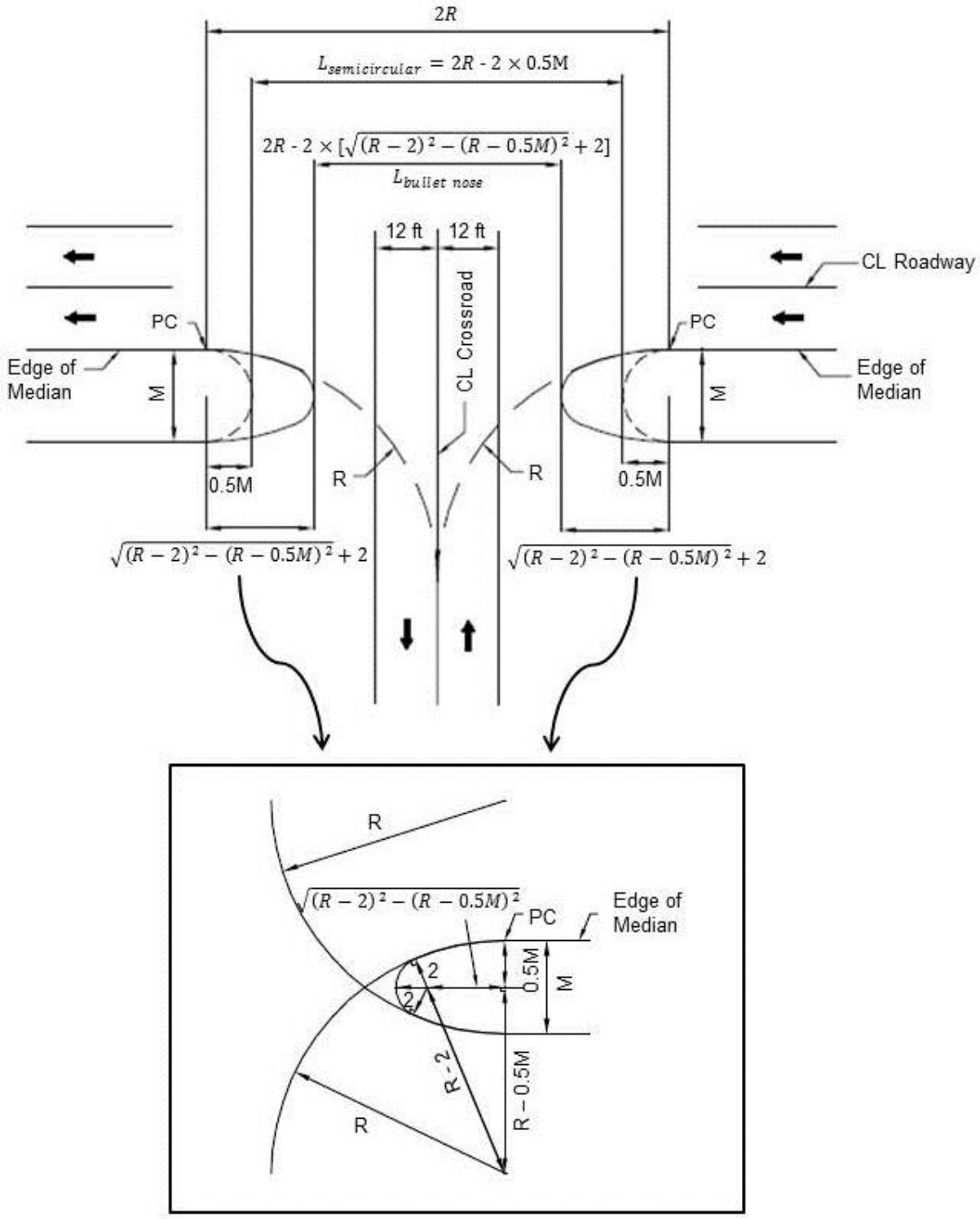


FIGURE 3. *Green Book* method for determining minimum median opening length (L) based on the median width (M) and shape of median ends (semicircular or bullet nose)

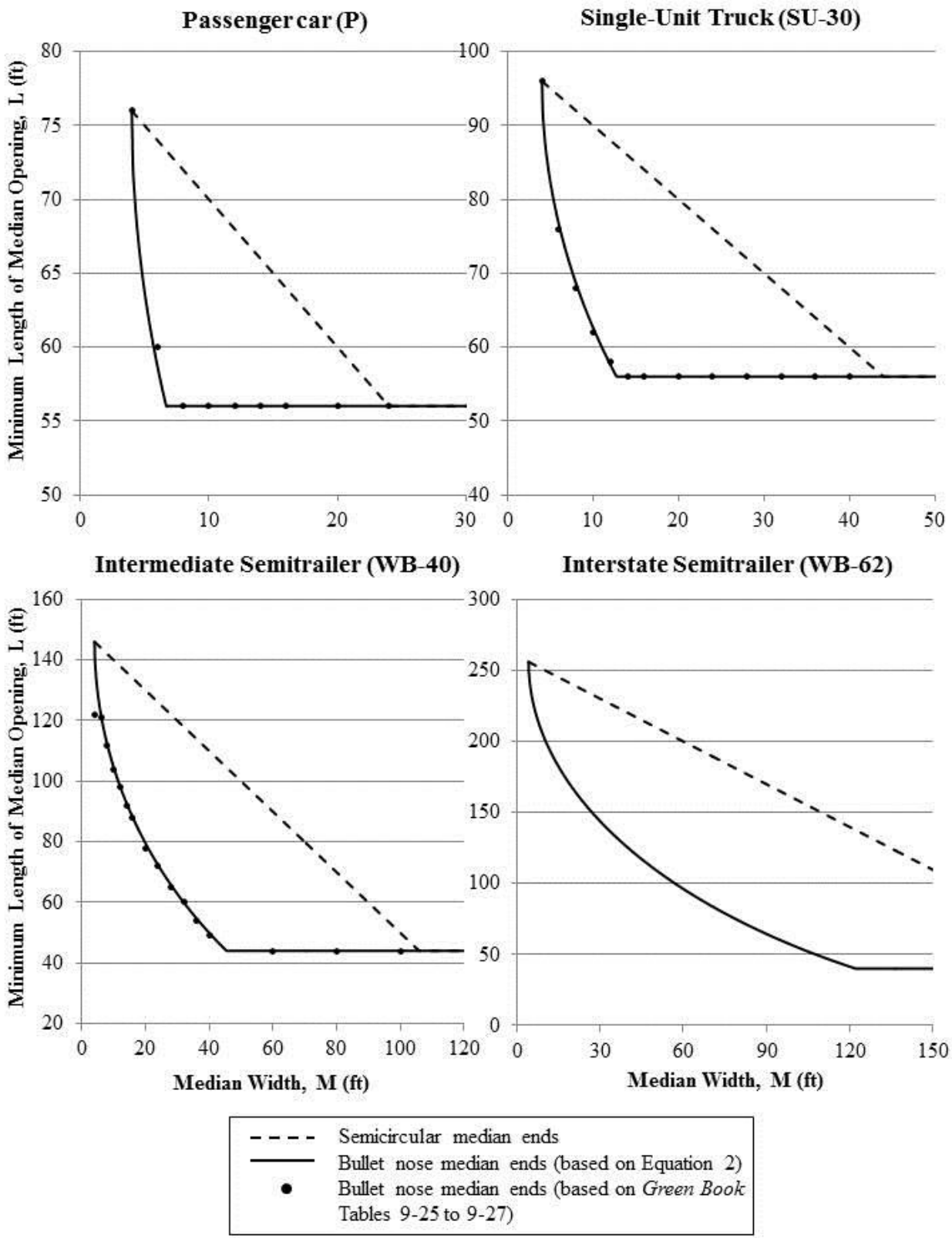


FIGURE 4. Minimum length of median opening calculated by Equations 1 and 2 along with the Green Book-recommended minimums in case of bullet nose median ends

As observed from Figure 4, for bullet nose median ends, the minimum median opening length determined from Equation 2 closely fits the recommended L values in Tables 9-25 to 9-27. The only exception is the required opening length for a 4-ft median and a WB-40 design vehicle: Table 9-27 recommends L = 122 ft whereas Equation 2 results in L = 146 ft. The 122 ft value in Table 9-27 may represent an error in the table, as the table value is different from the calculated value.

Finally, Section 9.8.3 of the *Green Book* states that "the length of the median opening should be as great as the width of the crossroad traveled way plus shoulders." This criterion should also be considered in determining the minimum length of median opening.

PRESENCE OF TURN LANES

As shown in Figure 2, the *Green Book* figures for minimum design of median openings display intersections with no left-turn lanes, in which case the median width is measured as the distance indicated by M. In presence of turn lanes, however, a major complexity arises in the measurement of median width: whether or not the median width (for which the minimum opening length is prescribed by Tables 9-25 to 9-27) should include the left turn lanes.

Despite no clarification in the *Green Book* section regarding minimum design of median openings, it is clear (see Figures 9-50 and 9-51, for example) that the *Green Book* definition of median width (M) includes turn lanes as part of the median (the median width is not reduced in the presence of turn lanes). However, the key question is whether the *Green Book* measurement of median width is appropriate for the minimum design guidelines for length of median opening.

Figure 5 shows a median opening with turn lanes on both approaches of the divided highway. The measurement of the median width according to the *Green Book* definition is indicated as M. Two new measurements of median width are introduced: M_1 and M_2, defined as the distance between the edge of the leftmost turn lane to the edge of the travelled way in the opposite direction. Such measurements of median width coincide with the MUTCD definition of median width (as illustrated in Figures 2B-15 and 2B-16 of the MUTCD). It is important to note that M_1 and M_2 are not necessarily equal in length because, for example, the two approaches may have unequal number of lanes.

As illustrated in Figure 5, presence of turn lanes results in asymmetrical control radius arcs for vehicles turning left from the divided highway into the crossroad and vice versa. Following the *Green Book* methodology, the minimum median opening length can be calculated as:

$$L = 2R - 0.5M_1 - 0.5M_2 \quad \text{(for semicircular median ends)} \qquad \text{(Eq. 3)}$$

$$L = 2R - \left[\sqrt{(R-2)^2 - (R-0.5M_1)^2} + 2\right] - \left[\sqrt{(R-2)^2 - (R-0.5M_2)^2} + 2\right]$$

(for bullet nose median ends) (Eq. 4)

Of course the minimum median opening length (L) can not be less than the overall minimums indicated in the *Green Book* Figures 9-55 to 9-58 (and Figure 4 in this paper). Intuitively, the L values in Tables 9-25 to 9-27 of the *Green Book* can be obtained as a special case of the equations above if $M_1 = M_2 = M$ (i.e., no turn lane). Therefore, by defining new measurements of median width and proposing mathematical equations (rather than tables) to determine the minimum length of median opening, the *Green Book* guidelines were generalized to be applicable for median openings with or without turn lanes.

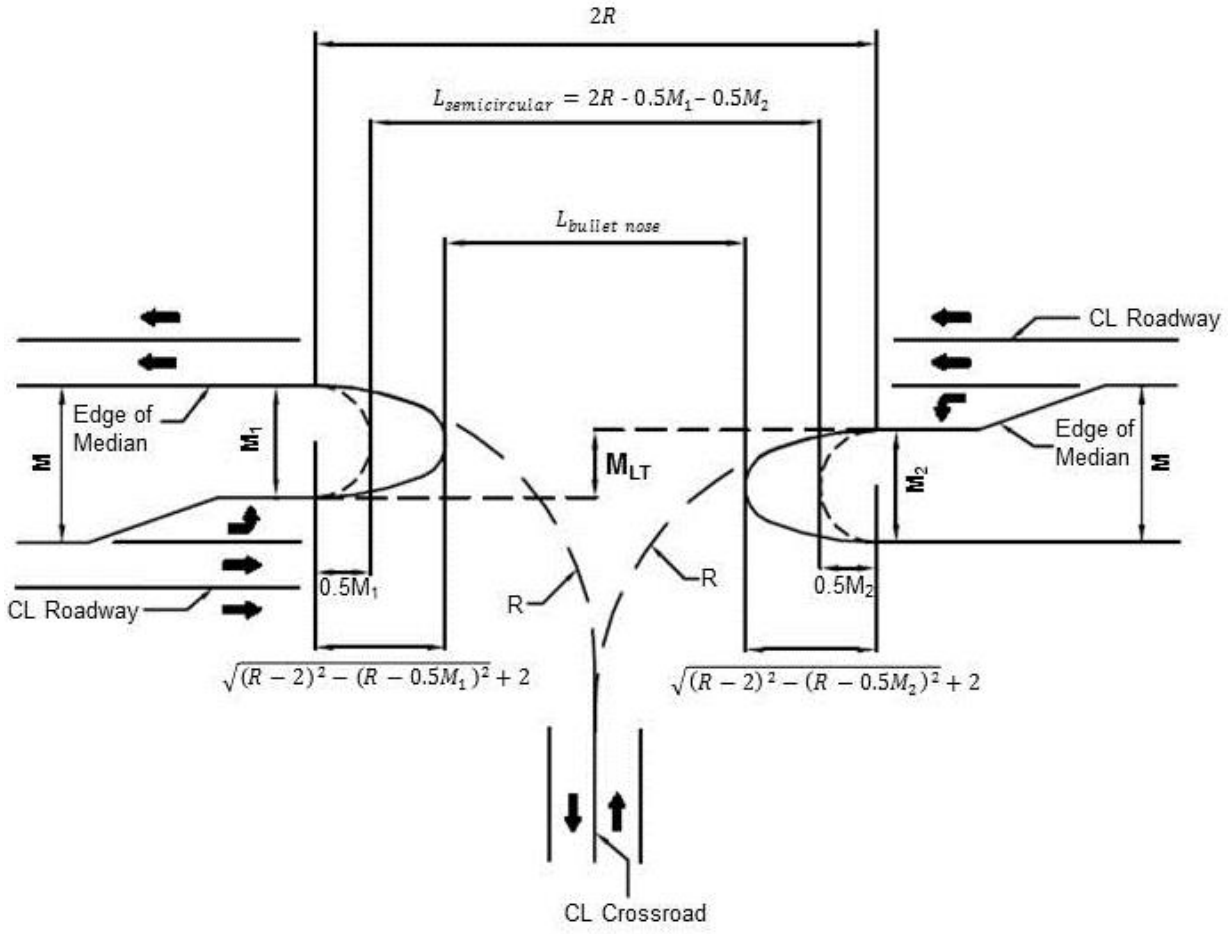
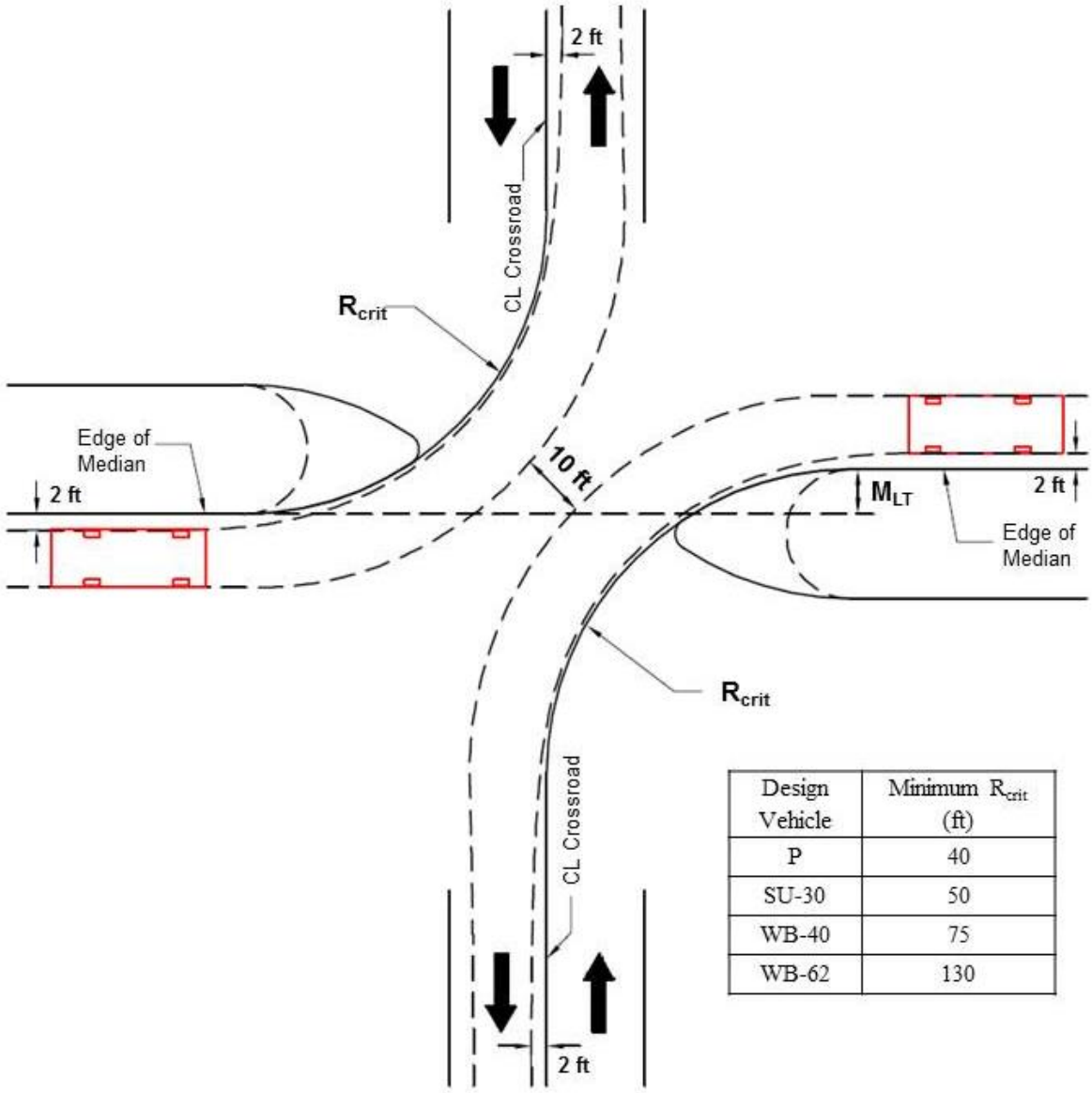


FIGURE 5. Minimum design of median openings in presence of turn lanes

SIMULTANEOUS LEFT TURNS

In the previous study (2), the authors described how both the *Green Book* and MUTCD definition of median width (indicated as M and M_1/M_2 in Figure 5, respectively) are irrelevant to the relative turning paths of opposing vehicles. The median width measurement that relates to the interaction between opposing vehicles left-turns is from the edge of the left-most turn lane in one approach of the divided highway to the edge of the left-most turn lane in the opposite direction. This measurement of median width (indicated in Figure 5 as M_{LT}) is used in this paper in replacement of the *Green Book* M to determine the minimum length of median opening required to accommodate simultaneous left turns. M_{LT} can have negative values if the extensions of left turn lanes on the two approaches overlap one another.

The approach is consistent with that of the *Green Book*; similar setting and assumptions are used. The critical control radius (R_{crit}) is defined as the minimum control radius that would accommodate simultaneous left turns with at least 10 ft of clear distance (as recommended by the *Green Book*). Figure 6 illustrates the setting used to find R_{crit} for a given M_{LT}. The critical radius should be greater than or equal to the control radii suggested by the *Green Book* for different design vehicles (i.e., 40 ft for P, 50 ft for SU-30, 75 ft for WB-40, and 130 ft for WB-62 design vehicles). Hence, the recommended guidelines can only be more conservative than those in the *Green Book*; the minimum opening length will be equal or greater than that recommended by the *Green Book*.



Design Vehicle	Minimum R_{crit} (ft)
P	40
SU-30	50
WB-40	75
WB-62	130

FIGURE 6. Determining the critical control radius to accommodate simultaneous left turns from divided highway

As stated by the *Green Book*, design for simultaneous left turns of trucks is generally impractical. However, in case the design vehicle is larger than a passenger car, the authors believe that it is reasonable to require the intersection geometry to accommodate simultaneous opposing turns of a design vehicle and a passenger car (rather than two design vehicles). Therefore, the critical control radii in this study are determined such that simultaneous opposing turns of a design vehicle and a passenger car could be accommodated.

In Figure 6, the edges of the turning vehicles paths are shown. The turning paths were simulated by an AutoCAD LISP (LISt Programming) routine, Turn.lsp (*4*), which tracks the vehicle block along the user-specified path. The software calculates the location of the vehicle at every user-specified step distance and then plots it. The calculation step distance of 0.5 ft was selected to ensure accuracy. Figure 7 shows an example of a passenger car turning path

simulated by Turn.lsp (*4*). The design vehicle blocks were selected from the AASHTO 2011 vehicle block library of Turn.lsp (*4*).

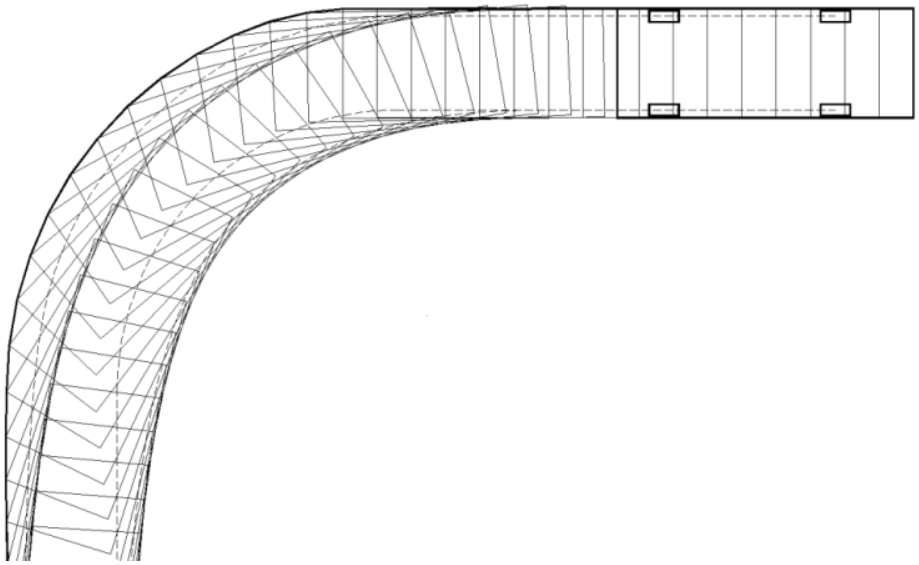


FIGURE 7. Turning path of a passenger car simulated by Turn.lsp (*4*) in AutoCAD

For consistency with the *Green Book*, the inner wheels of each turning vehicle are assumed to have a 2-ft clear distance from the median edge and centerline of the crossroad (as indicated in Figure 2 and 6). The critical control radius was determined for M_{LT} ranging from 0 to 100 ft (the longest range covered in the *Green Book* Tables 9-25 to 9-27) in increments of 10 ft. At every assumed M_{LT}, the critical control radius was determined with 0.1 ft accuracy by trial and error.

Figure 8 presents the results of the analysis. Using the *Green Book* fixed control radii, at some positive value of M_{LT}, simultaneous left turns can no longer be accommodated with at least 10 ft of clear distance (the *Green Book* control radii can accommodate simultaneous left turns for all negative values of M_{LT}). For larger M_{LT}s, the critical control radius to accommodate simultaneous turns will increase almost linearly with the increase in M_{LT}.

As Figure 8 indicates, accounting for simultaneous left turns is most important when the design vehicle is a passenger car because for M_{LT} greater than about 6 ft, the *Green Book* recommended control radius of 40 ft will fail to accommodate simultaneous left turns suitably. This reinforces the need to revise the *Green Book* guidelines.

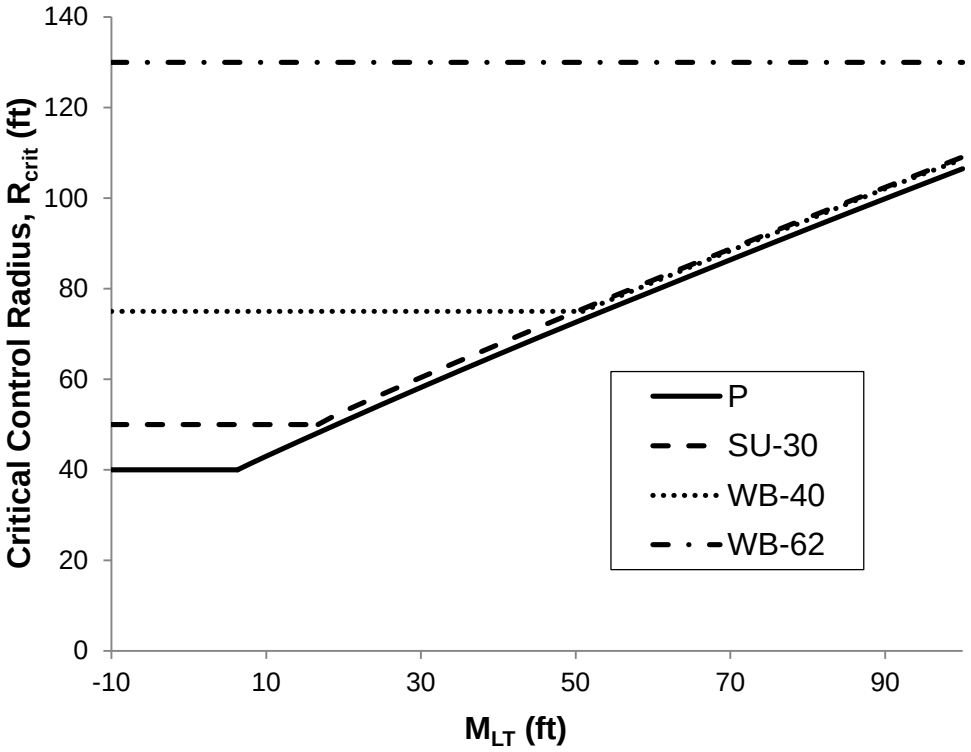


FIGURE 8. Critical control radius for accommodation of simultaneous opposing left turns

RECOMMENDED CHANGES TO GREEN BOOK

Based on the analysis presented in this paper, the following two-step method is recommended for use in the *Green Book* for determining the minimum length of median openings:

1) For divided highway intersections where simultaneous left turns are appropriate, the control radius should be determined from Figure 8 based on the median width measurement indicated as M_{LT} in Figure 5. If the crossroad is a low-volume highway and simultaneous left turns are not common, the *Green Book* fixed control radii can be used regardless of M_{LT}.
2) Minimum length of median opening (L) should be determined using the equations below:
   a. For semicircular median ends:

$$L = \text{MAX}\begin{bmatrix} 2R - 0.5M_1 - 0.5M_2 \\ 56 \text{ ft (P or SU-30), } 44 \text{ ft (WB-40), } 40 \text{ ft (WB-62)} \\ \text{width of crossroad traveled way plus shoulders} \end{bmatrix} \quad \text{(Eq. 5)}$$

   b. For bullet nose median ends:

$$L = \text{MAX}\begin{bmatrix} 2R - \left[\sqrt{(R-2)^2 - (R-0.5M_1)^2} + 2\right] - \left[\sqrt{(R-2)^2 - (R-0.5M_2)^2} + 2\right] \\ 56 \text{ ft (P or SU-30), } 44 \text{ ft (WB-40), } 40 \text{ ft (WB-62)} \\ \text{width of crossroad traveled way plus shoulders} \end{bmatrix} \quad \text{(Eq. 6)}$$

where R is the control radius determined from Figure 8 and M_1 and M_2 are median width measurements indicated in Figure 5. These equations combine the three criteria in the *Green Book* for determination of the minimum median opening length.

To define the different measurements of median width, it is recommended that Figure 5 of this paper be included in the *Green Book*. Reference to M_1/M_2 or M_{LT} as the 'median width' should be avoided to prevent confusion with the *Green Book* definition of median width (M).

The proposed method will remove the need for Tables 9-25 to 9-27 of the *Green Book*. However, Figures 9-55 to 9-58 should remain in the *Green Book* as they demonstrate how the minimum control radii are established for different design vehicles i.e., with the criterion that the design vehicle be accommodated suitably and occasional larger design vehicles be accommodated with some swinging wide. Nonetheless, the authors suggest that the median width measurement (M) in these figures be removed; the new method will depend on M_1/M_2 and M_{LT} which are defined in Figure 5.

Finally, it is important to note that the authors are not suggesting that the definition of median width in the *Green Book* should be altered. Different measurements of median width are appropriate for different applications. For example, the *Green Book* definition of median width (M) is relevant for guidelines on the design of median left-turn lanes, as provided in Section 9.7.3, M_1 and M_2 are relevant to the length of median ends (semicircular or bullet nose), and M_{LT} is the measurement that relates to the interaction between opposing left turns. However, the guidelines should emphasize the correct measurement of median width (through graphics) for each design applications.

CONCLUSIONS

The goal of this paper was to recommend revisions to the *Green Book* guidelines for the minimum length of median openings to account for simultaneous opposing left turns from the divided highway. An approach fully consistent with that used by the *Green Book* was followed and similar assumptions were used.

After a review of the *Green Book* guidance, it was revealed that the guidelines (summarized in Figures 9-55 to 9-58 and Tables 9-25 to 9-27) do not apply to median openings with turn lanes on the divided highway approaches. Using the *Green Book*'s own method (based on control radii for turning left from the divided highway into the crossroad and vice versa), this study generalized the *Green Book* guidelines for application to median openings with or without turn lanes. This was carried out by proposing equations (rather than tables) to determine the minimum length of median opening based on approach-specific measurements of median width (M_1 and M_2 in Figure 5) which do not include turn lanes.

To account for simultaneous left turns, the minimum control radius that would accommodate the opposing vehicles turning paths with at least 10 ft clear distance (as suggested by the *Green Book*) was determined for different design vehicles and median widths. Design vehicles turning paths were simulated by an LISP routine in AutoCAD (*4*). As design for simultaneous turns of opposing trucks is impractical, the minimum practical design was founded on the requirement that simultaneous turns of a design vehicle and an opposing passenger car (rather than two design vehicles) should be accommodated with at least 10 ft of clear distance.

The critical control radii for accommodation of simultaneous turns were determined as a function of a different measurement of median width (M_{LT} in Figure 5) which relates to the interaction between the opposing vehicles turning paths. The results suggested that minimum design according to Tables 9-25 to 9-27 of the *Green Book* can be insufficient for

accommodation of simultaneous turns especially when the design vehicle is a passenger car and a 40-ft control radius is assumed.

Based on the discussions and analysis in this paper, the authors proposed changes to the current *Green Book* guidelines on the minimum design of median openings. The proposed method will facilitate the median opening design as it combines the requirement for accommodation of left turns with the requirement for suitable accommodation of simultaneous left turns from opposing directions of the divided highway.

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